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BY JMarinda
DATE 5/11/06

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SALTONSTALL-KENNEDY PROJECT NA03NMF4270181

5/1/03- 10/31/05
02-NER-027

"AN ECONOMIC ANALYSIS OF AN ALTERNATIVE ATLANTIC SEA SCALLOP MANAGEMENT: SCALLOP ENHANCEMENT AND ROTATION OF FISHING AREAS"

FINAL REPORT

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EXECUTIVE SUMMARY

This final report summarizes the work conducted for the Saltonstall-Kennedy Grant Project NA03NMF4270181 originally entitled "An Economic Analysis of an Alternative Atlantic Sea Scallop Management: Harvesters Cooperatives and Scallop Enhancement". While the original proposal was focused on the role of harvesters cooperatives and scallop enhancement programs as management tools for the Atlantic sea scallop fishery, the issue of rotation of fishing areas kept emerging strongly from the beginning phases of the project. Our interest on the impact of rotational management was stimulated by the success of the temporary access programs to closed areas in Georges Bank during the years 2000 and 2004. Our decision to refocus our analysis was also motivated by the fact that the New England Fisheries Management Council (NEFMC) is currently under the process of implementing rotation of fishing areas as an integral part of management for the sea scallop resource. The latest amendment to the Sea Scallop Fishery Management Plan (FMP), Amendment 10, places great emphasis on the concept of rotation as the basis for improved stewardship of the resource.

The project was conducted in two separate but interrelated phases. In the first phase, a comprehensive model of the U.S. Atlantic sea scallop fishery was developed to evaluate the potential economic contribution of a large-scale stock enhancement program. The same model was used to evaluate the effectiveness of a simple mechanical rotation scheme of the closed areas in Georges Bank. Results in this phase of the project indicated that enhancement could potentially provide an effective buffer against natural fluctuations in scallop recruitment; however, achievement of these objectives would hinge on the development of a complex infrastructure of hatcheries, which in turn would require substantial investments from the public and/or the private sectors. In contrast, rotation of fishing areas was demonstrated to be a much simpler and highly effective management tool to improve utilization of the resource. More specifically, the model illustrated how many of the problems the fishery faced during the 1990s could have been mitigated by the demarcation of and controlled access to rotational fishing areas.

Given the preliminary results pointing out rotation of fishing areas as a robust management strategy, the second phase of the project focused on the development of a bioeconomic model aimed at the identification of optimal exploitation patterns for the sea scallop resource. Results unequivocally selected rotation of fishing grounds as the optimal management scheme. In addition, optimal rotation periods were determined separately for the Georges Bank and Mid-Atlantic Bight regions. A comparative analysis was also conducted to evaluate the relative effectiveness of the optimal pattern of rotational exploitation and a number of mechanical area rotation policies proposed by the NEFMC.

Findings from the first phase of the project were presented at the 2004 Biennial Meeting of the International Institute of Fisheries Economics and Trade (IIFET) held in Tokyo, Japan. A paper entitled "Designing Management Alternatives for the U.S. Atlantic Sea Scallop Fishery: Potential Contribution of Stock Enhancement Programs and Rotation of Fishing Areas" was prepared for the conference proceedings. Results from the second phase of the project were presented at the past 2005 Forum of the North American Association of Fisheries Economists (NAAFE) held in Vancouver, Canada. A manuscript summarizing these results is currently under preparation for publication in a Special Issue of *Land Economics*.

The results from our research are presented in this report in two separate parts, each corresponding to a different phase of the project. It is our belief that the research generated important implications towards improved management of the resource. In particular, we hope to have sufficiently stressed the importance of fully incorporating rotation of fishing areas in the management framework for Atlantic sea scallops. It is our conviction that our recommendations will contribute to preserve and enhance the conditions that have recently resulted in the most lucrative period in the history of the fishery.

PART I.

DESIGNING MANAGEMENT ALTERNATIVES FOR THE U.S. ATLANTIC SEA SCALLOP FISHERY: POTENTIAL CONTRIBUTION OF STOCK ENHANCEMENT PROGRAMS AND ROTATION OF FISHING AREAS

(Paper Presented at the 2004 IIFET Meeting)

1. INTRODUCTION

The Atlantic sea scallop, *Placopecten magellanicus*, is a bivalve mollusk that occurs on the eastern North American continental shelf. Major aggregations are found in the Mid-Atlantic from Virginia to Long Island, on Georges Bank, in the Great South Channel, and in the Gulf of Maine (NEFSC 2001). U.S. meat landings in 2003 exceeded 25,000 metric tons (MT), a new record, with ex-vessel revenues reaching almost $230 million, making the sea scallop fishery one of the most valuable in the northeastern United States, second only to lobster.

Landings from the U.S. fishery have been rather variable over the years (Figure 1). Poor recruitment and excessive fishing pressure led to a dramatic decline in commercial landings (below 8,000 MT) during 1993 and 1994. Roughly one-half of the productive scallop grounds in Georges Bank were closed in December 1994 and a myriad of effort-reduction measures have been implemented since then. Scallop biomass quickly rebuilt in the closed areas; it is estimated that over 80% of the sea scallop biomass in the U.S. portion of Georges Bank is now in the areas closed to fishing (NEFSC 2004). Two areas were also closed in the Mid-Atlantic between 1998 and 2001, and a controlled-access program has been operating in these two areas since 2001. Portions of the Georges Bank closed areas were also opened for limited scallop fishing during 1999-2001.

The depleted condition of the resource during the early 1990s stimulated interest on scallop enhancement as a viable means to increase fishery yields and protect the natural stocks. Scallop enhancement has evolved to become an integral part of resource management in countries such as Japan, New Zealand, and France (Howell *et al.* 1999). A government-supported demonstration project (The Seastead Project) was conducted in U.S. federal waters between 1995 and 1998 with mixed results. While direct bottom-seeding of juvenile scallops appeared to be economically feasible, culture in various cage structures generated negative returns (Smolowitz *et al.* 1998; Kite-Powell *et al.* 2003). The project leaders concluded that, despite the obvious importance of scallop enhancement for the future of the U.S. scallop fishery, excessive regulatory zeal, an unclear legislation framework, and conflicts with fishermen groups remained as major obstacles for enhancement and aquaculture activities in U.S. offshore waters.

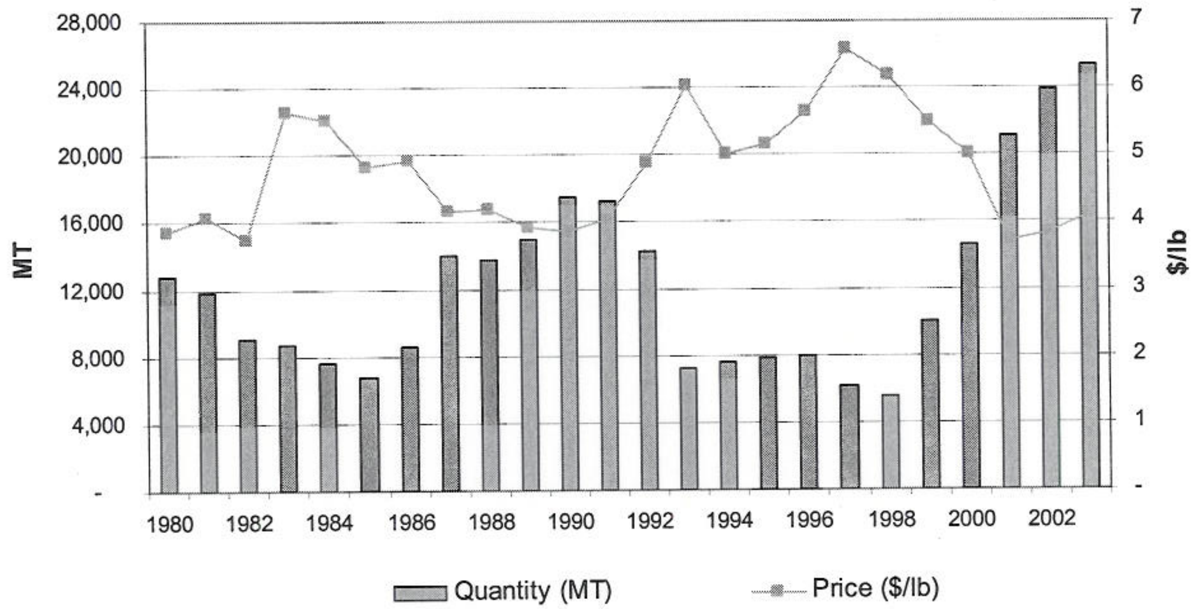


Figure 1. U.S. landings and average ex-vessel price of sea scallops. Source: NMFS (2005).

The landings of large quantities of scallops from the re-opened areas in Georges Bank during 1999-2001 pointed out the benefits of a rotational system of closed areas. In fact, Amendment 10 of the Atlantic Sea Scallop Fishery Management Plan outlined the characteristics of a rotational closure program to be initiated in Georges Bank and the Mid-Atlantic region in the summer of 2004 (NEFMC 2004a). The concept in its simple form is that areas containing beds of small sea scallops are closed before the scallops begin experiencing fishing mortality and then the areas re-open for fishing when the scallops are larger, boosting meat yield.

In practice, this simple concept will prove difficult to apply because it will require consideration of the smallest practical areas to close, the duration of the closures, and the fishing mortality to be applied when the areas re-open. Despite these difficulties, the New England Fishery Management Council (NEFMC) has proposed a fully-adaptive rotation system of flexible-boundary areas. Based on the results from government- and industry-supported resource surveys, the NEFMC would consider areas for closure when the expected increase in exploitable biomass in the absence of fishing mortality exceeds 30% per year, and re-open to fishing when the annual biomass increase in the absence of fishing mortality is less than 15% per year. This strategy would protect areas with young, fast-growing scallops, and re-direct fishing pressure to areas with older, slower growing scallops. The NEFMC has proposed to use ten-minute squares (each about 75 square nautical miles) as the basis for the evaluation of contiguous blocks that may close to protect young scallops. A ten-minute square implies a level of micro-management that is currently not possible to achieve with the existing government surveys. It is still unclear whether industry-supported surveys will provide sufficient information for implementation of this fully-adaptive rotation system.

Given the potential benefits that could be derived from stock enhancement and rotation of area closures, the goal of this research is to conduct a comparative analysis of these management options relative to the "status quo" management system based on static closure areas with temporary access programs. The study develops an age-structured population dynamics model that simulates the evolution of scallop stocks in various management regions reflecting the effects of natural processes (recruitment, natural mortality) and fishery management decisions on stock biomass and the level of commercial landings. The model was used to develop estimates of the net revenues that could be generated by 1) a stock enhancement program supported by a system of hatcheries in the northeast and mid-Atlantic regions, and 2) a simplified rotational management system for the closed areas in Georges Bank. Results of this study will provide us with an assessment of the potential gains to be realized with each management alternative, thereby contributing to our knowledge base for improved management of the Atlantic sea scallop resource.

2. METHODS

Our modeling approach is similar to that used in population dynamics models developed by biologists at the Northeast Fisheries Science Center, National Marine Fisheries Service (NMFS/NEFSC) (NEFMC 2000; 2003). These models have been successful in forecasting the increases in sea scallop abundance, landings, and catch rates that have been observed in the last several years. For our purposes, the Georges Bank (GB) and Mid-Atlantic Bight (MAB) stock areas were sub-divided in 11 management sub-regions: seven in GB (four closed areas and three open areas) and four in the MAB (two closed areas and two open areas). Table 1 lists the management sub-regions and their respective areas in square nautical miles (nm^2) (NEFSC 2001).

Table 1. Management sub-regions in the Georges Bank and Mid-Atlantic Bight stock areas.

		Name	Area (nm^2)
Georges Bank	Closed Areas	Closed Area I	673
		Closed Area II – Northern Part	863
		Closed Area II – Southern Part	994
		Nantucket Light Ship Closed Area	828
	Open Areas	North Edge and Peak Open Area	989
		South Channel Open Area	1,373
		Southeast Part Open Area	1,562
Mid Atlantic Bight	Closed Areas	Hudson Canyon South Closed Area	1,461
		Virginia Beach Closed Area	130
	Open Areas	Delmarva Open Area	1,411
		New York Bight Open Area	5,356

The model uses a difference equation approach where time is partitioned into discrete time steps $t_1, t_2, \ldots$, with a time step of length $\Delta t = t_{k+1} - t_k = 0.042$ years (approximately 14 days). Population is tracked in each management sub-region i and time t by population vectors $\mathbf{p}(i,t) = (p_1, p_2, \ldots, p_n)$, where p_j represents the density of scallops in the j^{th} size class in region i at time t. Catches at each size class in the i^{th} region and k^{th} time step are represented by a landings vector $\mathbf{h}(i, t_k)$ calculated as

$$\mathbf{h}(i,t_k) = [I - e^{(\Delta t H(i,t_k))}]\,\mathbf{p}(i,t_k) \qquad \text{(Eq. 1)}$$

where I is the identity matrix and H is a diagonal matrix whose j^{th} diagonal entry h_{jj} is given by

$$h_{jj} = \begin{cases} 0 & \text{if } s(j) \le s_d \\ -F_c(i,t_k)\dfrac{[s(j) - s_{\min}]}{(s_{full} - s_{\min})} & \text{if } s_d < s(j) < s_{full} \\ -F_c(i,t_k) & \text{if } s(j) \ge s_{full} \end{cases} \qquad \text{(Eq. 2)}$$

where $s_{\min}$ is the minimum size at which a scallop is vulnerable to the gear, s_{full} is the size at which a scallop is fully vulnerable to the gear, s_d is the cull size ($\ge s_{min}$) below which scallops are discarded, and $F_c\,(i, t_k)$ denotes the capture fishing mortality rate suffered by a full recruit in area i at time t_k (NEFMC 2000).

Shell-height-meat-weight conversion parameters are used to estimate the vector of meat weights $\mathbf{m}(i)$. The landings $L(i, t_k)$ for the i^{th} region and k^{th} time step are calculated using the equation

$$L(i,t_k) = A_i\,\mathbf{h}(i,t_k) \bullet \frac{\mathbf{m}(i)}{(we_i)} \qquad \text{(Eq. 3)}$$

where A_i and e_i represent the area and dredge efficiency in the i^{th} region, respectively, and w is the tow path area of the survey dredge.

Scallops of shell height less than a minimum size s_d are assumed to be discarded and suffer a discard mortality rate of d (20%). Some scallops not actually landed may suffer mortality due to incidental damage from the dredge. Incidental fishing mortality was modeled as $F_I = 0.175\ F_c$ in Georges Bank and as $F_I = 0.03\ F_c$ in the Mid-Atlantic regions (NEFMC 2003).

Scallops grow according to a Von Bertalanffy equation so that their shell height $s(t)$ at age t (in years) is given by

$$s(t) = L_{\infty}[1 - e^{(-k[t-t_0])}] \qquad \text{(Eq. 4)}$$

Equation (4) can be used to construct a matrix G, which specifies the fractions of each size class that remains in that size class, or grows to other size classes, in a time Δt. The population dynamics of scallops in each size class can be summarized in the equation

$$\mathbf{p}(i, t_{k+1}) = \rho_i + G\, e^{(-MH)\Delta t}\, \mathbf{p}(i, t_k) \qquad \text{(Eq. 5)}$$

where ρ_i denotes recruitment into the j^{th} size class at time t and M is a matrix containing the natural mortality, discard fishing mortality, and incidental fishing mortality parameters. The population and harvest vectors are converted into biomass by using the shell-height meat-weight relationship:

$$W = e^{[a+b\ln(s)]} \qquad \text{(Eq. 6)}$$

where W is the meat weight of a scallop of shell height s. Commercial landing rates (LPUE) were estimated using an empirical function based on the observed relationship between annual landing rates and survey exploitable numbers per tow (NEFMC 2003). A modified Holling Type-II model was used so that the landings per unit of effort (number of scallops landed per day at sea) L will depend on scallop exploitable biomass B according to the formula:

$$L = \frac{\alpha\, B}{\sqrt{\beta^2 + B^2}} \qquad \text{(Eq. 7)}$$

The parameters α and β need to be modified according to crew size. Starting in 1994, the maximum crew size allowed in scallop vessels was seven men. Before then, an average scallop vessel would have a crew of 9-10 men. Table 2 summarizes all model parameters.

Table 2. Parameters of the age-structured model for Atlantic sea scallops in Georges Bank and the Mid-Atlantic Bight stock areas.

Parameter	Description	Value
Δt	Simulation time step	0.042 years
L_∞	Maximum shell height	152.46 mm (GB), 151.84 (MAB)
K	Growth parameter	0.4 y^{-1} (GB), 0.23 y^{-1} (MAB)
m	Natural mortality rate	0.1 y^{-1} across all size classes
a	Shell height/meat weight parameter	-11.6038 (GB), -12.2484 (MAB)
b	Shell height/meat weight parameter	3.1221 (GB), 3.2641 (MAB)
s_0	Initial shell height of recruit	40 mm
s_{min}	Minimum size retained by gear	65 mm
s_{full}	Size for full retention by gear	90 mm
s_d	Maximum size discarded	80 mm
d	Mortality of discards	0.2
e	Dredge efficiency	0.5 (GB), 0.7 (MAB)
α	LPUE/biomass relationship (seven-man crew)	49,056
β	LPUE/biomass relationship (seven-man crew)	102.8

Status Quo Management

A *status quo* scenario was developed by recreating the conditions of the fishery during the period 1990-1999. The NEFSC/NMFS conducts periodic assessments of the sea scallop population in U.S. federal waters through Stock Assessment Workshops (SAW). The 32nd SAW report (2001) compiled the results from the annual government-supported surveys and provided a complete overview of the status of the resource in each management sub-region between 1979 and 2000 (NEFSC 2001). The annual surveys provide complete estimates of biomass, population numbers, and length frequencies. Information from the 1990 survey was used to establish initial conditions for the age-structured model. Because the surveys describe the status of the resource at the beginning and end of each year, the capture fishing mortality rate $F_c\,(i, t_k)$ and the recruitment rate ρ_i in the population model were adjusted so that the number of individuals and distribution by size classes predicted by the model coincided with the results from the annual surveys. It should be noted that the biological surveys are subject to sampling variability, thus the derived estimates can not be interpreted as exact measures of fishing pressure and recruitment events. However, these estimates do reflect stock trends and provide an adequate characterization of a *status quo* management scenario that can be used for further comparisons with other management alternatives.

Economic Sub-model

The population dynamics model predicts annual landings for the entire fishing fleet, therefore its was necessary to develop ex-vessel price equations to describe the interactions between ex-vessel price, the level of domestic landings, and other price determinants such as disposable income per capita and price and quantity of scallop imports. Monthly landings data (1998-2003) provided by the NEFSC/NMFS were used to develop price equations for six different size categories (under 10, 11-20, 21-30, 31-40, 41-50, and 61+ counts). Upon examination of alternative models, ex-vessel price of sea scallops in each size category was postulated to be a function of domestic landings and average price of all imports of Canadian scallops to the northeast region.

Specification and estimation of cost equations are also necessary for analyzing policy options. A cost equation developed by the NMFS/NEFSC was used to estimate per-vessel annual operating costs of scallop fishing (*OPC*) as a function of vessel crew size (*CREW*), vessel size in gross tons (*GRT*), and vessel days at sea (*DAS*) (NEFMC 2003). The equation is

$$\underset{}{Log\,(OPC)} = \underset{(6.31)}{4.6130} + \underset{(3.34)}{0.2531}*Log\,(CREW) + \underset{(3.46)}{0.2743}*Log\,(GRT) + \underset{(8.79)}{1.1134}*Log\,(DAS) \quad \text{(Eq. 8)}$$

n = 69, adj R-sq = 0.58, D-W = 1.97, t-value in parentheses.

Stock Enhancement Program

Stock enhancement in Japan is mostly done through collection of wild spat and bottom re-seeding in protected bays. The government-funded Seastead Project relied on collection of juvenile scallops in the groundfish closed areas to re-seed the growout locations. Given our incomplete knowledge of "hot spots" collection areas and the inherent variability of wild spat abundance, it appears that a large-scale enhancement program conducted in U.S. federal waters would have to depend on hatchery-supplied seed. That has been the case in places such as the Bay of Brest in France, where hatchery production contributes a significant portion of landings from the scallop fishery (Boncoeur *et al.* 2003).

The stock enhancement scenario assumes that a system of hatcheries is in place to support enhancement activities in Georges Bank and the Mid-Atlantic Bight. Five hatcheries in each stock area with an individual production capacity of 100 million juveniles per year (shell height of 25 mm) would meet the seeding requirements for approximately 14.58 nm^2 at a stocking density of 10 juveniles/m^2. Assuming a growout cycle of five years and rotation of seeded areas, the total area allocated for the enhancement program would be nearly 73 nm^2 (14.58 nm^2 *5) in both Georges Bank and the Mid-Atlantic Bight. The five seeding areas would be initially stocked between 1990 and 1994, with the first harvest occurring in 1995 (corresponding to the area seeded in 1990). The model assumes annual harvests until the end of the modeling period, in 1999. Additional simulations of this scenario were run assuming growout cycles of 3 and 5 years.

The enhancement program is assumed to take place in any of the closed areas in GB and the MAB. Harvesting of seeded areas would be done through a cooperative agreement among fishermen. The cost of the enhancement program is mostly limited to the purchase of hatchery seed ($0.02 per seed) (Penney and Mills 2000).

Rotational Management of Closed Areas

The last scenario proposes a simple rotation scheme for the groundfish closed areas in Georges Bank. It is assumed that the areas are closed in January 1990 (rather than December 1994) and each area is sub-divided in four equal sections. Every year one of the sections in each area is re-opened for fishing ($F_c = 0.32$). Rotation takes place between 1990 and 1999. It is assumed that fishing activity within the re-opened sections does not affect recruitment in the surrounding areas.

In practice, it may be difficult to implement such a rotation system given that the closed areas are also governed by regulations pertaining to other species. This practicality was overlooked since the purpose of the analysis was simply to demonstrate the potential benefits associated with rotational fishing.

3. RESULTS

Figure 2 compares the gross revenue predicted by the *status quo* management scenario with the actual revenue from the fishery, as reported by NMFS (NMFS 2005). Despite the uncertainties and sampling variability associated with the resource surveys, the age-structured model reflects to a considerable extent the major trends in domestic landings. Gross revenue from the fishery was in the proximity of $150 million during 1990-1992. Poor recruitment caused in part by overfishing translated into a significant decline in landings in 1993 and 1994. Gross revenue did not exceed $100 million between 1995 and 1998 given the overfished condition of the resource and the exclusion of vessels from the closed areas in GB. The surge in landings (see Figure 1) and revenue in 1999 was due to the temporary re-opening of GB CLII-S. Gross revenue predicted by the model in 1998 and 1999 was lower than what was observed because the survey data suggested unusually high fishing mortalities in the Mid-Atlantic region in those particular years.

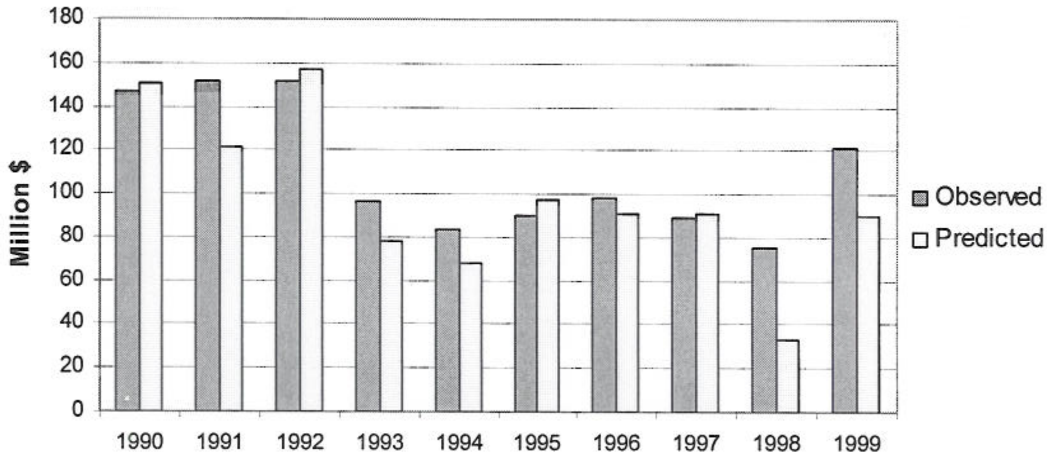


Figure 2. Observed and Predicted Gross Revenues for the U.S. Atlantic Sea Scallop Fishery.

Stock Enhancement Program

Table 3 summarizes the results of the stock enhancement scenario. Net Present Value (computed with respect to 1990 at a discount rate of 7%) of the stream of annual revenues (net of operating costs) between 1990 and 1999 would be highest for the four-year growout cycle (near \$560 million). Assuming a recovery rate (i.e., dredge efficiency) of 50 and 70% in GB and MAB (see Table 2), annual harvest from the ranched areas would be 2,138 and 1,442 MT, respectively. Production would be greater in GB because of the superior growth rates (Table 2). Comparatively, the estimated NPV for the *status quo* management scenario was \$503,672,250.

Table 3. Results from the stock enhancement scenario.

	3-year cycle		4-year cycle		5-year cycle	
	GB	MAB	GB	MAB	GB	MAB
Annual production from ranched areas (MT)	1,571	939	2,138	1,442	2,474	1,882
Size count (#/lb)	11-20 & 21-30	31-40 & 41-50	11-20	21-30 & 31-40	11-20	11-20 & 21-30
Number of harvests in 10 years	7		6		5	
NPV (10 years, 7%)	\$511,303,447		\$555,808,909		\$553,665,185	

Figure 3 shows the relative contribution of enhancement to the total quantity harvested by the fishery. Enhancement represented between 30-40% of total landings during 1993-1999, years during which natural recruitment in the fishery was particularly low. An enhancement program has also the potential to reduce the economic impact on the fleet caused by the closure of some of the most productive areas.

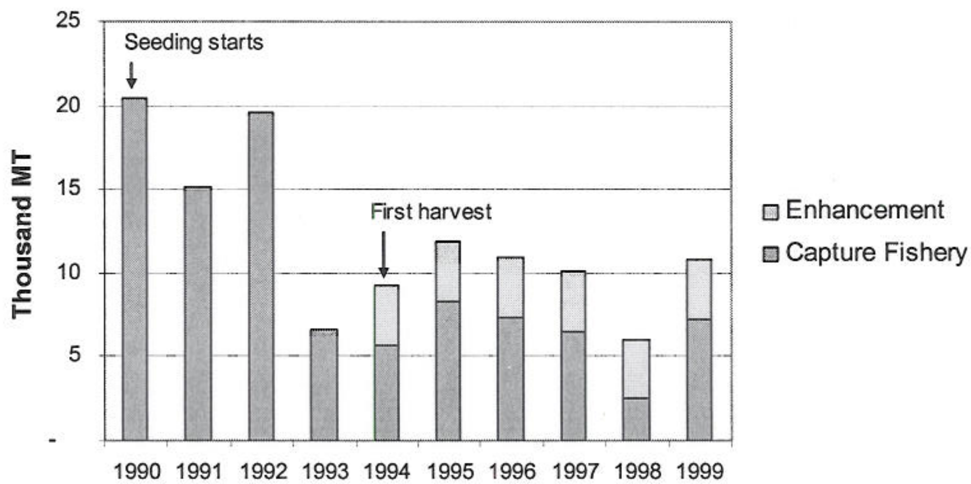


Figure 3. Relative contribution of enhancement to total landings from the Atlantic sea scallop fishery (1990-1999). Growout cycle of cultured scallops is four years.

Rotational Management of Closed Areas

Although landings during 1990-1992 significantly decreased as compared to the *status quo* scenario, rotational harvesting of the groundfish closed areas resulted in increased yields in the years thereafter (Figure 4). The estimated NPV for the rotational management scenario was $614,366,072, i.e., 22% higher than the *status quo*.

As with the network of closures, rotational management leads to rapid increases in the biomass of scallops in the protected areas (Figure 5). If closures had taken place in 1990, biomass within the closed areas in GB might have reached 18 kg/tow by 1998, i.e., 80% higher than in the *status quo* scenario.

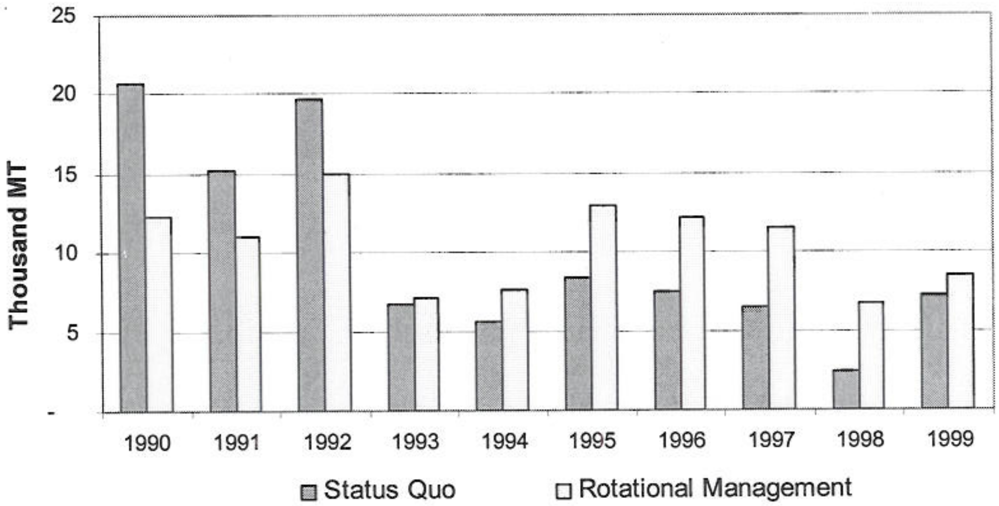


Figure 4. Total landings from the Atlantic sea scallop fishery under *status quo* management and rotational harvesting of groundfish closed areas.

4. DISCUSSION

Stock Enhancement Program

Scallop enhancement techniques have been developed over the years to the extent that sea ranching programs contribute a significant portion of fishery landings in countries such as Japan, France, and New Zealand. Scallop aquaculture in North America is still in the initial stages of development with the most important accomplishments in hatchery and growout technologies having occurred primarily in Canada (Penney and Mills 2000). Enhancement programs have been successful in Japan because highly efficient techniques have been developed for collection of wild spat and because the costal topography in the fishing regions provide sufficient protected locations for the deployment of culture structures. In contrast, the most productive areas in the U.S. are found in offshore locations subject to strong currents and harsh weather conditions during the winter months. Researchers from the Seastead Project reported severe damage to some of their cage and buoy structures due to the strong currents in the area (in some instances, damage was also inflicted by vandals) (Smolowitz *et al.* 1998).

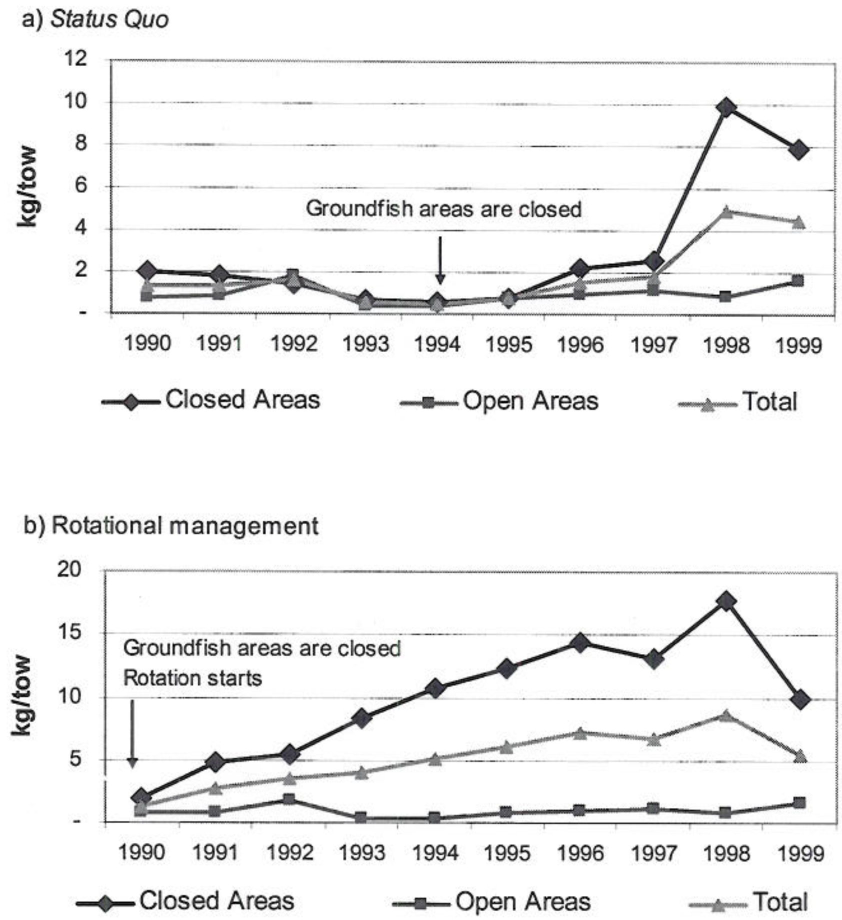


Figure 5. Biomass of Atlantic sea scallops in closed and open areas of Georges Bank: a) *Status Quo* scenario; b) Rotational management of groundfish closed areas.

At present, it appears that bottom-seeding of juvenile scallops in "reserve" areas is the only feasible form of scallop aquaculture in U.S. offshore waters. Still, this approach would be dependent on a consistent supply of hatchery-produced seed. Scallop hatchery technology in North America is still evolving. Some important breakthroughs have been achieved at facilities in Martha's Vineyard (Massachusetts) (MVSG 1996), but hatchery technology is more advanced in Canada. Currently, there are operating hatcheries in Newfoundland with a production capacity of 20 million scallops per year (Scallop Culture Consultancy, Undated).

The enhancement scenario in our model assumed a hatchery production capability that is not yet existent in the U.S (1 billion 25-mm seed per year). However, provided there were a sufficient degree of commitment on part of the government and the private sector, such production capability could potentially be developed. Our results show that enhancement activities would yield on average about 3,580 MT per year, assuming a 4-year growout cycle. Average landings between 1980 and 2003 were 12,253 MT (Figure1), therefore enhancement could potentially contribute on average about 23% of the total fishery yield. Unlike the wild-based fishery, production from the enhanced areas would be much more stable, removing the uncertainty associated with natural recruitment.

Despite our projections, it is unlikely that scallop enhancement becomes an essential component of fishery management in the U.S. to the extent it has in places such as the Bay of Brest in France or the Southern Scallop Fishery in New Zealand. This is in part because these fisheries are relatively small, with annual yields ranging between 150-350 MT in France and 400-700 MT in New Zealand (Boncoeur *et al.* 2003; Arbuckle 2000). The associated fishing communities are also small, which among other things facilitates coordination for seeding and harvesting of the common grounds.

Finally, the 10-year NPV estimate for the 4-year grow-out cycle was slightly higher than for the 5-year cycle. This difference was mainly due to the relatively short time period considered for the analysis, i.e, it does not necessarily mean that it is more advantageous to harvest a greater number of 4-year scallops as compared to a smaller number of larger 5-year scallops. If the analysis were expanded to 20 years, the difference in NPV would be negligible. In contrast, harvest value is lower if the growout cycle is limited to three years.

Rotational Management

The most interesting result from the analysis was that overall landings from the closed areas in Georges Bank were greater under rotational management as compared to *status quo* management even when the available fishing area was much smaller under the former scenario. In concrete numbers, the comparison is as follows: under *status quo* management, total area available for fishing in the closed areas between 1990 and 1999 was approximately 16,790 nm^2

(the four closed areas add up to 3,358 nm^2 and were open for five years between 1990 and 1994). Under rotational management, 25% of the closed areas was available for fishing every year between 1990 and 1999, therefore total fished area in the 10 years was 8,395 nm^2. Despite this disparity, total landings (all areas in GB and MIB) in the 10 years under *status quo* management was 99,977 MT while landings amounted to 105,038 MT in the rotational fishing scenario.

Figure 5 suggests an explanation to this result: the closed areas were heavily fished during 1990-1994 even though biomass was very low (less than 2 kg/tow). Under these conditions, landings remained low while the cost of fishing increased. Under rotational management, access to the scallop beds was granted only until biomass had been rebuilt, which made fishing much more efficient. Harvests that were missed in the previous three years were rapidly captured during the re-opening periods.

Rotation of fishing areas appears as a simple yet effective method to rationalize fishing effort in the scallop fishery. It re-directs fishing pressure in a manner that is much more consistent with the biological characteristics of the resource. There is little doubt that the fishery will benefit from the recent shift in management towards rotational harvesting of fishing grounds. On the other hand, the adaptive approach with flexible-boundary areas recommended by the New England Fishery Management Council (NEFMC) will probably demand more information than what the biological surveys will be able to provide. Also, boundaries that are constantly moving may generate some confusion among fishermen. To begin with, rotational management of fishing areas with fixed boundaries would provide more than satisfactory results.

PART II.

IMPROVING UTILIZATION OF THE ATLANTIC SEA SCALLOP RESOURCE: OPTIMAL ROTATION OF FISHING GROUNDS

(Paper Presented at the 2005 NAAFE Forum)

1. INTRODUCTION

The Atlantic sea scallop, *Placopecten magellanicus*, is a bivalve mollusk that occurs on the eastern North American continental shelf. Major aggregations are found in the Mid-Atlantic from Virginia to Long Island, on Georges Bank, in the Great South Channel, and in the Gulf of Maine (NEFSC 2001). U.S. meat landings in 2003 exceeded 25,000 metric tons (MT), a new record, with ex-vessel revenues reaching almost $230 million, making the sea scallop fishery one of the most valuable in the northeastern United States, second only to lobster.

Landings from the U.S. fishery have fluctuated considerably over the years. Landings increased substantially after the mid-1940's, with peaks occurring around 1960, 1978, 1990, and in the most recent period (2001-2004). The U.S. portion of Georges Bank witnessed a dramatic decline in productivity during 1993, with landings remaining low until 1998. Historically, the Mid-Atlantic Bight area has been less productive than Georges Bank; however, there has been an upward trend in both recruitment and landings in the area since the mid-eighties (NEFSC 2004). Scientists agree that unusually strong recruitment in the Mid-Atlantic Bight has been a key contributor to the record landings achieved in the most recent years.

Sea scallop fisheries in the U.S. Exclusive Economic Zone (EEZ) are managed under the Atlantic Sea Scallop Fishery Management Plan (FMP), initially implemented in May 1982. During the initial years regulation was primarily based on a minimum average meat weight requirement for landings. The near-collapse of the fishery in Georges Bank during the mid-1990s prompted drastic changes in management philosophy. The Amendment #4 to the FMP (NEFMC 1993), implemented in 1994, shifted management away from meat count regulations to effort control measures, including incrementally increasing restrictions on days-at-sea (DAS), minimum ring size, and crew limits. In addition, approximately one-half of the productive scallop grounds on Georges Bank were closed in December 1994. In the Mid-Atlantic, two areas were closed for three years starting in 1998 to protect aggregations of small scallops. Area closures had an immediate effect on scallop abundance and biomass; for example, it is estimated that over 80% of the sea scallop biomass in the U.S. portion of Georges Bank is currently in areas closed to fishing (NEFSC 2004). Portions of Georges Bank closed areas were temporarily opened for limited scallop fishing during 1999-2001, resulting in the landings of exceptional amounts of very large scallops. Remarkable landings have also been achieved from controlled-access programs to the closed areas in the Mid-Atlantic Bight since 2001.

The success of the temporary access programs led to the formulation of a new set of regulations, Amendment #10, implemented in 2004 (NEFMC 2004a). This amendment proposes a spatially-based management system, with provisions and criteria for new rotational closures, and separate days-at-sea allocations for reopened closed areas and general open areas. Under this amendment, restricted access to portions of two of the Georges Bank closed areas during the fall of 2004 was approved. Preliminary reports indicate that the reopened areas have again yielded large amounts of "frisbee-sized" scallops (McGovern 2004). Amendment #10 also introduced new gear regulations to improve selectivity towards larger scallops and to reduce the amount of associated bycatch.

Sea Scallops and Rotational Management

There is already considerable evidence that rebuilding of sea scallop biomass in heavily overfished areas can be conducted much more efficiently through area closures than with effort control regulations such as meat count requirements or limited crew sizes. For example, biological surveys conducted in 1998 indicated that total and harvestable scallop biomasses were 9 and 14 times denser, respectively, in closed than in adjacent open areas in Georges Bank (Murawski *et al.* 2000). Evidence clearly suggests that the sea scallop fishery would benefit greatly from a formal "area rotation" scheme of fishing grounds. This same approach has been proposed or is being used for other sedentary species such as sea urchins, sea cucumbers, corals, and abalone (Lai and Bradbury 1998; Heizer 1993; Caddy 1993; Botsford *et al.* 1993; Sluczanowski 1984). Sea scallops appear to be ideal candidates for rotational fishing because 1) they have low mobility, moving at most a few miles per year; 2) they grow quickly and are relatively long-lived; and 3) they exhibit low natural mortality (around 10% per year).

In its simplest form, the concept of rotational management proposed by Amendment 10 implies the closure of areas containing beds of small sea scallops before they experience fishing mortality and the reopening of areas for fishing when the scallops are larger, boosting meat yield. In practice, this simple concept will prove difficult to apply because it will require consideration of the smallest practical areas to close, the duration of the closures, and the fishing mortality to be applied when the areas re-open. Despite the information gaps, the New England Fishery Management Council (NEFMC) has proposed a fully-adaptive rotation system of flexible-boundary areas. Based on the results from government- and industry-supported resource surveys, the NEFMC would consider areas for closure when the expected increase in exploitable biomass in the absence of fishing mortality exceeds 30% per year, and re-open to fishing when the annual biomass increase in the absence of fishing mortality is less than 15% per year. This strategy would protect areas with young, fast-growing scallops, and re-direct fishing pressure to areas with older, slower growing scallops. The NEFMC has proposed to use ten-minute squares (each about 75 square nautical miles) as the basis for the evaluation of contiguous blocks that may close to protect young scallops. A ten-minute square implies a high resolution level for management that is currently not possible to achieve with the existing government surveys. It is still unclear whether industry-supported surveys will provide sufficient information for final implementation of this fully-adaptive rotation system.

Given the complexity of the rotation system contemplated by Amendment 10, the NEFMC proposed a simpler scheme of mechanical rotation via Framework Adjustment (FA) 16 (NEFMC 2004b) for portions of three closed areas in Georges Bank. Under this strategy, access was allowed to the Nantucket Lightship Area and Closed Area II in the fall of 2004. In 2005, the Nantucket Lightship Area would close, while Closed Areas I and II would become accessible for scallop fishing. The general idea is to implement a three-year rotation cycle that would open access to scallops in two of three groundfish closed areas each year. Thus, in 2006 Closed Area

II would close, while the Nantucket Lightship Area and Closed Area I would become accessible. This three-year cycle might be reinitiated in 2007. The order of rotation and target mortality rates specified in FA 16 are given in Table 4.

Table 4. Fishing mortality targets for a mechanical area rotation strategy proposed in Framework Adjustment 16 (NEFMC 2004b). $F = 0.2$ is approximately the continuous (i.e. every year) fishing mortality that maximizes yield-per-recruit, or F_{max}.

Fishing Year	Closed Area I	Closed Area II	Nantucket Lightship Area
2004	Closed	0.2	0.2
2005	0.2	0.2	Closed
2006	0.2	Closed	0.2
2007	Same as 2004	Same as 2004	Same as 2004

The simplicity of the rotation scheme proposed in FA 16 suggests that research efforts should be directed first at the improvement of strategies for mechanical rotation before engaging in ambitious (and difficult to implement) rotation systems based on fully-adaptive flexible boundaries. There is no question that the latter system would lead to a more rational utilization of the resource, but its complex logistics may ultimately render this approach unfeasible. Optimization of mechanical rotation strategies might serve as a basis for the design of simple but highly effective rotational systems that are much easier to administer. With this idea in mind, the goal of this paper is to develop a bioeconomic model of Atlantic sea scallops that takes into consideration the biological characteristics of the resource to determine optimal patterns of exploitation. The model will seek to describe the population dynamics of a plot of sea scallops in both Georges Bank and the Mid-Atlantic Bight regions and determine the optimal levels of annual exploitation rates leading to maximization of the Net Present Value of the fishery for a period of 30 years (NPV_{30}).

Evidence from the temporary access programs to closed areas suggests that rotational management may lead to increased efficiency in the fishery; therefore, it is anticipated that the simulation model will specify a staggered schedule of closures and reopenings for the plot of sea scallops. One of the most important insights to be obtained from the model is related to the optimal duration of closures for the fishery. This result would provide an important benchmark to evaluate the effectiveness of the three-year cycles contemplated by FA 16.

The following section of this paper explains the bioeconomic model for Atlantic sea scallops. Most of the model parameters were obtained from a number of studies conducted by scientists at the Northeast Fisheries Science Center, National Marine Fisheries Service (NMFS/NEFSC). This section will be followed by a discussion of the results of various model simulations. Particular emphasis will be given to the implications of our empirical results with respect to the rotation systems proposed in Amendment 10 and FA 16.

2. METHODS

Our modeling approach is similar to that used in population dynamics models developed by biologists at the NMFS/NEFSC. These models have been successful in forecasting the increases in sea scallop abundance, landings, and catch rates that have been observed in the last several years (NEFMC 2004a).

Briefly, the objective of the model is to keep track of the number, size composition, and biomass of two hypothetical stocks of scallops – placed in Georges Bank and the Mid-Atlantic Bight, respectively – for a period of 30 years. The main processes affecting the standing biomass are natural recruitment, natural mortality, and fishery exploitation. The model distributes the population of fully-recruited scallops across 5-mm size classes, or bins (size refers to the height of the shell in mm). The smallest size class is the 40-45-mm bin, corresponding to young adults (about 2.2 and 2.5 years-old in Georges Bank and the Mid-Atlantic Bight, respectively). The largest size class is the 145-150-mm bin, occupied by the oldest scallops. Scientists at the NEFSC routinely model recruitment as a stochastic process[1], assuming a log-normal distribution for each management sub-area. In our model, recruitment of new members into the adult population is assumed to occur at a constant rate R, corresponding to a weighed

[1] Studies have repeatedly indicated that a stock-recruitment relationship is difficult to identify in either Georges Bank or the Mid-Atlantic (NEFSC 2004).

average of the historical time series between 1992 and 2000 for both Georges Bank and the Mid-Atlantic Bight (NEFSC 2001). We assumed a constant rate of recruitment to keep the model within tractable proportions for the optimization routine process. In a subsequent stage, Monte Carlo simulation analyses were conducted to evaluate the effect of stochastic variation in recruitment rates on the results of the model.

The model uses a difference equation approach where time is partitioned into discrete time steps t_1, t_2, …, with a time step of length $\Delta t = t_{k+1} - t_k = 0.042$ years (approximately 14 days). Population is tracked at each time t by population vectors $\mathbf{p}(t) = (p_1, p_2, \dots, p_n)$, where p_j represents the density of scallops in the j^{th} size class at time t. Catches at each size class at each k^{th} time step are represented by a landings vector $\mathbf{h}(t_k)$ calculated as

$$\mathbf{h}(t_k) = [I - e^{(\Delta t H(t_k))}]\,\mathbf{p}(t_k) \qquad \text{(Eq. 9)}$$

where I is the identity matrix and H is a diagonal matrix whose j^{th} diagonal entry h_{jj} is given by

$$h_{jj} = \begin{cases} 0 & \textit{if } s(j) \le s_d \\ -F_c(t_k)\dfrac{[s(j) - s_{\min}]}{(s_{full} - s_{\min})} & \textit{if } s_d < s(j) < s_{full} \\ -F_c(t_k) & \textit{if } s(j) \ge s_{full} \end{cases} \qquad \text{(Eq. 10)}$$

where $s_{\min}$ is the minimum size at which a scallop is vulnerable to the gear, s_{full} is the size at which a scallop is fully vulnerable to the gear, s_d is the cull size ($\ge s_{min}$) below which scallops are discarded, and $F_c(t_k)$ denotes the capture fishing mortality rate suffered by a full recruit at time t_k (NEFSC 2001).

Conversion parameters are used to estimate the vector of meat weights $\mathbf{m}$ (representing the meat weights at shell height s) by means of the following shell-height meat-weight relationship:

$$W = e^{[a+b\ln(s)]} \qquad \text{(Eq. 11)}$$

where W is the meat weight of a scallop of shell height s.

Thus, the landings $L(t_k)$ for the k^{th} time step can be calculated as

$$L(t_k) = A\mathbf{h}(t_k) \bullet \frac{\mathbf{m}}{(we)} \qquad \text{(Eq. 12)}$$

where A denotes the total area of the plot of scallops (in square nautical miles, nm^2), e represents the dredge efficiency, and w is the tow path area of the dredge (estimated as 8/6080 nm^2).

Captured scallops of shell height less than a minimum size s_d are assumed to be discarded and suffer a discard mortality rate of d estimated at 20% in NEFSC (2001). Some scallops not actually landed may suffer additional mortality due to incidental damage from the dredge. Incidental fishing mortality was modeled as $F_I = 0.175\ F_c$ in Georges Bank and $F_I = 0.03\ F_c$ in the Mid-Atlantic Bight (NEFMC 2003).

Growth of scallops is modeled with a Von Bertalanffy equation:

$$s(t) = L_\infty[1 - e^{(-K[t-t_0])}] \qquad \text{(Eq. 13)}$$

where $s(t)$ is shell height at age t (in years), K is the growth parameter, and L_∞ represents the maximum shell height.

Equation (13) can be used to construct a matrix G specifying the fractions of each size class that remains in that size class, or grows to other size classes, in any given time interval Δt. The population dynamics of the stock of scallops can be summarized with the equation

$$\mathbf{p}(t_{k+1}) = \rho + G\, e^{(-MH)\Delta t}\ \mathbf{p}(t_k) \qquad \text{(Eq. 14)}$$

where ρ denotes recruitment into the j^{th} size class at time t and M is a matrix containing the natural mortality, discard fishing mortality, and incidental fishing mortality parameters.

Landings per unit of effort (LPUE) were estimated using an empirical function based on the observed relationship between annual landing rates and survey exploitable numbers per tow[2] (NEFMC 2004a). A modified Holling Type-II model was used so that the landings per unit of effort (number of scallops landed per day at sea) L will depend on scallop exploitable biomass B according to the formula:

$$L = \frac{\alpha B}{\sqrt{\beta^2 + B^2}} \qquad \text{(Eq. 15)}$$

where α and β are constants.

Table 5 summarizes all model parameters. Most values were taken from the 32nd Northeast Regional Stock Assessment Workshop report (NEFSC 2001).

Table 5. Parameters of the age-structured model for Atlantic sea scallops in Georges Bank and the Mid-Atlantic Bight stock areas.

Parameter	Description	Value
Δt	Simulation time step	0.042 years
L_∞	Maximum shell height	152.46 mm (GB), 151.84 (MAB)
K	Growth parameter	0.4 y^{-1} (GB), 0.23 y^{-1} (MAB)
m	Natural mortality rate	0.1 y^{-1} across all size classes
R	Annual number of recruits per tow	129 y^{-1} (GB), 58 y^{-1} (MAB)
a	Shell height/meat weight parameter	-11.6038 (GB), -12.2484 (MAB)
b	Shell height/meat weight parameter	3.1221 (GB), 3.2641 (MAB)
s_0	Initial shell height of recruit	40 mm
s_{min}	Minimum size retained by gear	65 mm
s_{full}	Size for full retention by gear	88 mm
s_d	Maximum size discarded	80 mm
d	Mortality of discards	0.2
e	Dredge efficiency	0.5 (GB), 0.7 (MAB)
α	LPUE/biomass relationship (seven-man crew)	49,056
β	LPUE/biomass relationship (seven-man crew)	102.8

[2] In this paper, the term "tow" refers to the standard area unit used in the NEFSC biological surveys. It corresponds to approximately 8/6080 $nm^2 \approx 0.0013\ nm^2$.

Economic Sub-model

The economic analyses conducted by the NEFMC (e.g., NEFMC 2004a; 2003) routinely include pricing models to obtain more accurate estimates of the impact of regulatory measures on profitability of the fishery. Pricing equations were not used in our analysis because the model is concerned only with the population dynamics of a relatively small plot of scallops. In other words, we assume that fishermen behave as price takers. We also assume that a different price is received for each of the following size categories: under 10, 11-20, 21-30, 31-40, 41-50, 51-60, and 61+ counts[3]. Monthly landings data (1998-2003) provided by the NMFS/NEFSC were used to compute ex-vessel nominal prices for each size category, which were subsequently expressed in their equivalent 1996 constant prices. The averages of the time series of constant prices were used as representative values for each size category (Table 6). A consistent premium was assumed across meat counts, i.e., larger scallops command higher prices.

Table 6. 1996 constant ex-vessel prices assigned to six different size categories in the bioeconomic model of the Atlantic sea scallop fishery. Based on monthly landings data (1998-2003) provided by the NMFS/NEFSC.

Size category	Price ($/lb)
Under 10	5.91
11-20	4.69
21-30	4.36
31-40	4.27
41-50	4.05
51-60	3.80
61+	3.65

The plots of scallops were assumed to be managed under sole ownership. Variable costs of fishing were estimated using a cost equation developed by the NMFS/NEFSC (Gautam and Kitts 1996; Edwards 1997). Per-vessel annual operating costs (OPC) in 1996 constant prices are a function of vessel crew size (CREW), vessel size in gross tons (GRT), and vessel days at sea (DAS). The equation is

[3] Counts refer to the number of meats per pound.

$$Log\,(OPC) = 4.6130 + 0.2531{*}Log\,(CREW) + 0.2743{*}Log\,(GRT) + 1.1134{*}Log\,(DAS) \quad \text{(Eq. 16)}$$
$$(6.31) \quad (3.34) \qquad\qquad (3.46) \qquad\qquad (8.79)$$

n = 69, adj R-sq = 0.58, D-W = 1.97, t-value in parentheses.

Crew size was assumed to be seven, the maximum allowed under Amendment 4. Vessel size was specified to be 166.2 gross tons, which is a common tonnage in the fishery. The number of days at sea is directly related to landings per unit of effort. An important feature of the model is that vessels capture a greater number of scallops per unit of time when the biomass of the resource is at a high level, thereby reducing the harvesting cost per scallop (see Eq. 15).

The model assumes scallop plots are 680 nm^2 each, and the fishing fleet is composed of 20 vessels in each stock area. These parameters are arbitrary as they do not affect the qualitative character of the results, only the scale of the payoffs to the fishery.

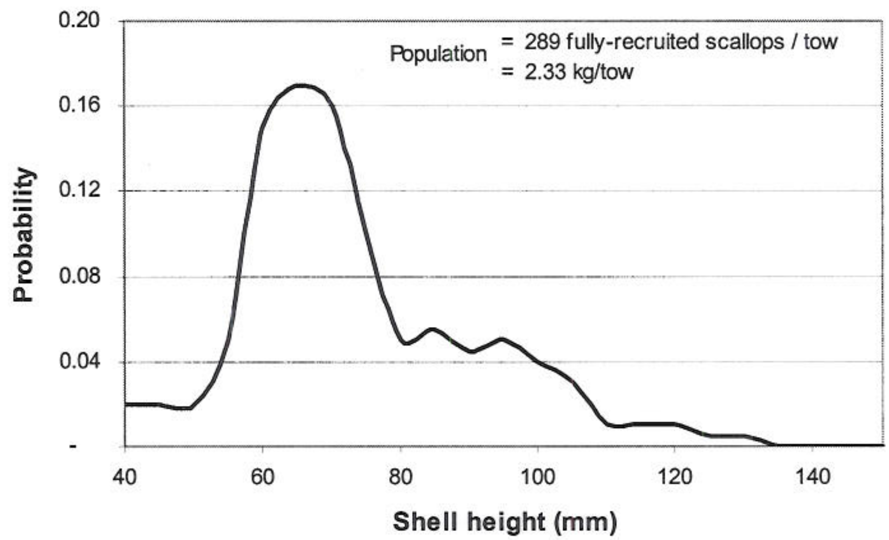
In summary, the population of scallops increases due to natural recruitment and declines due to natural mortality and fishery exploitation. The objective of the sole owner is to maximize the stream of annual net revenues (gross revenues minus operating costs) over the 30-year period. The control variable is the level of fishing pressure F_c that is selected at the beginning of each year (see Eq. 10).

MATLAB codes were written to conduct the simulations. Biomass and shell height composition data from the NEFSC scallop biological surveys for Closed Area I (Georges Bank) in 1990 (NEFSC 2001) were used as initial conditions for the simulations in both Georges Bank and the Mid-Atlantic Bight (Figure 6). The *fmincon* solver was used to find a global maximum for the NPV of the fishery (a "real" discount rate[4] of 5% was assumed) in both stock areas. Given the complexity of the model, upper and lower bounds were imposed on the control

[4] Because prices and costs are expressed as 1996 constant prices, the discount rate is assumed to be unadjusted for inflation.

variable F_c to facilitate the optimization process. Exploitation rates were restricted to fluctuate between zero (closure of the fishery) and one (maximum fishing pressure allowed in the model)[5].

Figure 6. Shell height composition data from NEFSC sea scallop surveys illustrating the state of the resource for Closed Area I in the Georges Bank stock area during 1990 (Source: NEFSC 2001). These composition data were used as initial conditions for simulations in both Georges Bank and Mid-Atlantic Bight stock areas.



It is noted that the model contains simplifying assumptions on aspects such as recruitment, pricing, and composition of the fleet, because our primary interest was to focus the optimization process on crucial biological characteristics such as scallop growth, gear selectivity, incidental fishing mortality, and the effect of higher biomass on LPUE. Our intuition suggested that these were the key features in the search for optimal exploitation strategies for the resource.

[5] It is recalled that the fishery exploitation rate F_c corresponds to the exponent in a model of exponential decay. Thus, a exploitation rate $F_c = 1$ implies that approximately 65% of the harvestable biomass is extracted every year.

3. RESULTS AND DISCUSSION

Georges Bank

Table 7 presents the selection of annual fishing mortality rates (F_c) for the plot of scallops in Georges Bank. A quick glance at the results reveals the evidence for rotational fishing. The beginning biomass at Year 1 (2.33 kg/tow) reflects the depleted condition of the resource in Closed Area I during 1990 as reported by the 32nd SAW (NEFSC 2001). Given that the resource is depleted in Year 1, the model proceeds to close down the fishery from Year 1 through Year 5. The fishery is reopened in Years 6, 7, and 8. Fishing occurs at a moderate rate in Year 6 (F_c = 0.268), but intense exploitation takes place in Years 7 and 8 (F_c = 1). A second cycle is initiated in Year 9 and extends through Year 16. The fishery is closed for six years to let biomass rebuild and intense harvesting at F_c = 1 occurs in the last two years of the cycle (Years 15 and 16). A third cycle extends from Years 17 to 23 (with a five-year closure and two years of intense exploitation) while the fourth and final cycle begins with a four-year closure (Years 24 through 27) and ends with three years of exploitation at F_c = 1.

Table 7. Optimal Levels of Fishery Exploitation (F_c) for a plot of Atlantic Scallops in the Georges Bank Region.

Year	F_C	Year	F_C	Year	F_C	Year	F_C
1	0	9	0	17	0	24	0
2	0	10	0	18	0	25	0
3	0	11	0	19	0	26	0
4	0	12	0	20	0	27	0
5	0	13	0	21	0	28	0.527
6	0.268	14	0.074	22	1	29	1
7	1	15	1	23	1	30	1
8	1	16	1				

The first and second production cycles (from Years 1 through 8 and 9 through 16) suggest an optimal pattern of rotational harvesting for Georges Bank consisting of a 6-year closure period followed by two years of intense harvesting. The slightly shorter closure periods identified in the third and fourth production cycles (Years 1- through 23 and 24 through 30) reflect the need to accommodate these two cycles within the 30-year time frame of the simulation.

These results are important not only because they specify the optimal duration of closures and re-opening periods in the Georges Bank fishery, but also because they clearly reveal that the pattern of pulse fishing is better suited to the characteristics of the resource than exploitation at a constant fishing rate. Our results support the general assertion that rotational harvesting is a more sensible management strategy for sedentary species as compared to continuous exploitation under open-access conditions (Caddy and Seijo 1998; Caddy 1993). The estimated NPV_{30} obtained from a 680-nm^2 plot is approximately \$324 million under the rotational harvesting schedule shown in Table 7. In contrast, the NPV_{30} of the fishery is only \$278 million (-14%) if the stock is exploited under a constant annual rate $F_c = 0.2$. The latter number is recommended by the NEFMC as a target fishery mortality rate corresponding to 80% of the rate that maximizes yield-per-recruit for the Atlantic sea scallop fishery in Georges Bank (NEFSC 2001).

As one of several alternatives considered in their analysis of rotational management, Amendment 10 has proposed a ramped rotation approach whereby a fishing area is closed for three years and subsequently reopened for three years at exploitation rates $F_c = 0.32$, 0.40, and 0.48, respectively. One important property of this approach is that the time-averaged fishing mortality is precisely 0.2, the target rate. In our simulation, this ramped rotation scheme leads to an NPV_{30} of \$294 million, which is 9% less that the maximized NPV_{30}. It should be noted that the time-averaged fishing mortality rate is 0.3 under the optimal rotational schedule of Table 7.

Two main factors drive the selection of rotational harvesting strategies in our simulations:

1) fishery closures and subsequent reopenings lead to the harvest of larger scallops, which command a higher price per pound. Our results indicate that over 80% of landings in each harvesting cycle are composed of the largest two size categories of scallops (under 10 and 11-20) (Table 8).

2) fishing costs per pound decline significantly when biomass has been allowed to accumulate. This is directly related to the empirical relationship between landings per unit of effort and exploitable numbers per tow demonstrated in Equation 15 and further illustrated in Figure 7. A higher LPUE leads to a reduction in the number of fishing days required to land a given quantity of scallops, which in turn results in considerable savings in operating costs. For example, setting $F_c = 0.2$ from Year 1 through Year 6 results in a total of 311 DAS for any given vessel during this six-year period. The same poundage can be landed by setting $F_c = 0$ from Year 1 through Year 5, and having $F_c = 0.52$ in Year 6. In the last case, however, only 253 DAS per vessel are required.

Table 8. Size composition of landings (percentage) in each harvesting cycle of the bioeconomic model of Atlantic sea scallops in the Georges Bank region.

Size category	Cycle 1 (Years 6, 7, 8)[a]	Cycle 2 (Years 15, 16)	Cycle 3 (Years 22, 23)	Cycle 4 (Years 28, 29, 30)
Under 10	47 %	47 %	41 %	35 %
11-20	39 %	41 %	45 %	48 %
21-30	7 %	7 %	7 %	9 %
31-40	4 %	4 %	4 %	5 %
41-50	2 %	2 %	2 %	2 %
51-60	1 %	1 %	1 %	1 %
61+	0 %	0 %	0 %	0 %
Total	100 %	100 %	100 %	100 %

[a] The numbers in parenthesis indicate the years in which harvesting takes place.
Numbers may not add up due to rounding.

Figure 7. Empirical relationship between landing rates, expressed as number of scallops caught per day (NLPUE) and survey exploitable numbers per tow (NEFMC 2004a).

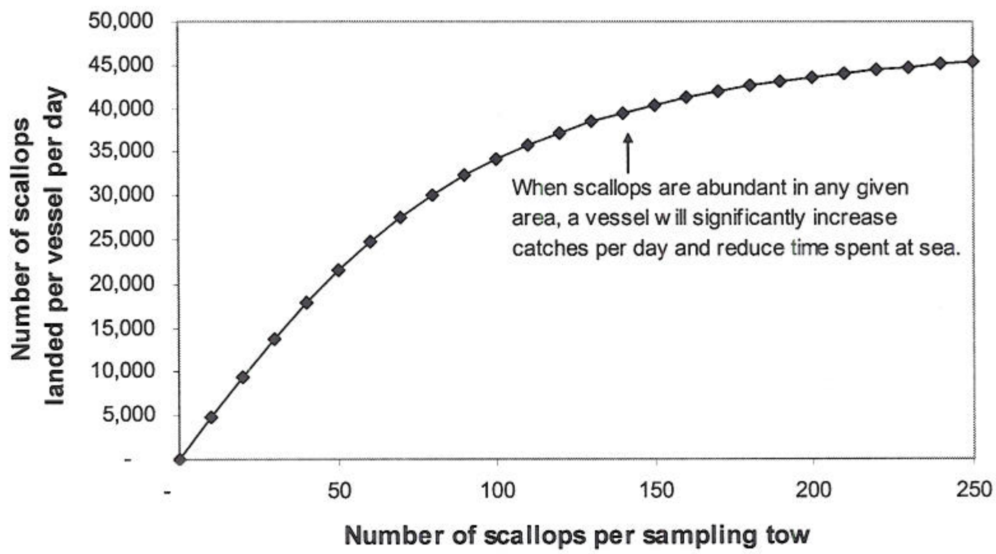
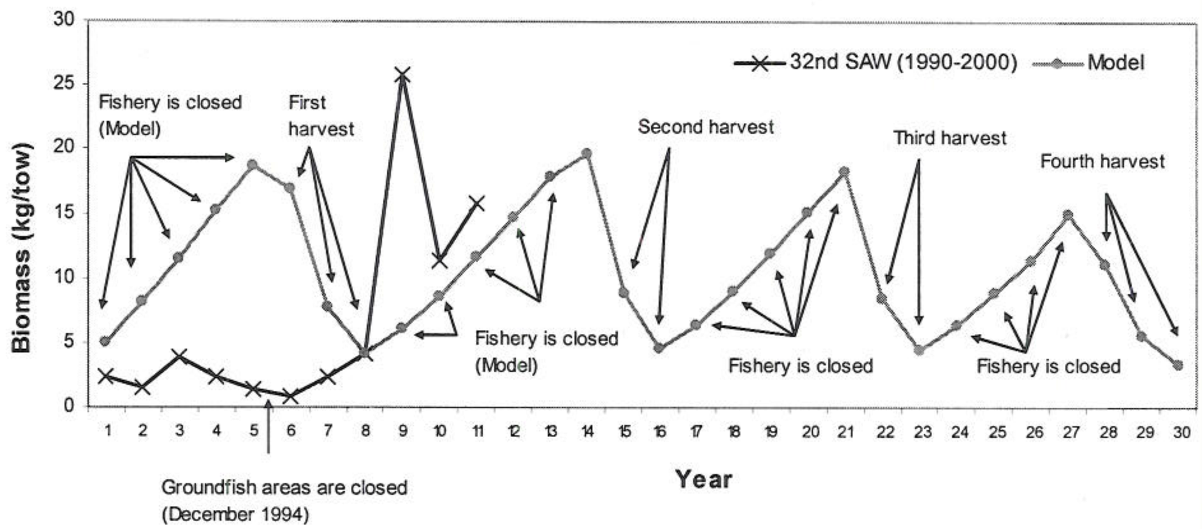


Figure 8 compares biomass at the end of the year (kg/tow) as predicted by the model to the average of survey biomass data reported by the 32nd SAW (NEFSC 2001) for Closed Area I in Georges Bank. It is reminded that the model was initialized with the 32nd SAW data corresponding to 1990. While the model recommends closing the fishery immediately, the actual resource was heavily exploited during the early 1990s, with survey biomass routinely under 5 kg/tow. The area closure in December 1994 led to substantial increases in survey biomass almost immediately. Sampling conducted in 2000 indicated biomass in Closed Area I was over 15 kg/tow. On the other hand, the biomass series predicted by the model clearly illustrates the selected pattern of pulse fishing, with only four major harvest events during the 30-year period and area closures within harvests. Biomass in the model is allowed to fluctuate between 4 and 20 kg/tow.

Several researchers had already pointed out the potential benefits of rotational fishing for Atlantic sea scallops. Myers *et al.* (2000) and Hart (2003) concluded that rotational fishing had the potential to generate increased yield and biomass-per-recruit for sea scallops compared to nonrotational fishing. In addition, Myers *et al.* (2000) indicated that rotational harvesting may contribute to reduce the effects of uncertainty over indirect fishing mortality. Both studies, however, focused on the biological implications of rotational management, giving no consideration to the economic advantages inherent to rotation of fishing areas. Both studies, therefore, probably undervalued the full potential of rotation as a fisheries management strategy.

Figure 8. Comparison of time series of biomass (kg/tow). The starred line represents data from the 32nd SAW report (2001) corresponding to the average of survey trend data for Closed Area I in Georges Bank (1990-2000). The dotted line depicts biomass at the end of the year as simulated by the model.



Myers *et al.* (2000) argued that a rotational period close to 6 years, with a fishing mortality of around 0.5 upon reopening of the area, would result in a close to maximum average yield per recruit and would maintain spawning biomass at acceptable levels. Our results indicate that the fast growth of scallops in Georges Bank support higher fishing rates upon re-opening of areas (F_c = 1 for two years). This result is also based on the assumption that recruitment remains close to the historical average. As mentioned previously, there is yet no clear evidence of a spawning stock – recruitment relationship for Atlantic sea scallops (NEFSC 2004); therefore, we did not assume a strong adverse effect on recruitment due to the reopenings of fishing grounds. Even if such effect existed, the subsequent multi-year closure would contribute to boost recruitment in the fishery.

Hart (2003) also suggested that a rotation period of 6.1 would be near optimal for Atlantic sea scallops in Georges Bank. She also mentioned that gains from rotation would be modest unless the closure was timed to optimally exploit an unusually large class. As explained previously, Hart (2003) analysis most likely underestimated the benefits of rotation because no consideration was given to premiums paid for larger scallops or the savings in fishing costs resulting from extraction at larger biomasses. Nevertheless, Hart (2003) was emphatic in recommending rotational management as part of a precautionary strategy because it could help alleviate the effects of growth and recruitment overfishing.

Mid-Atlantic Bight

Table 9 presents the selection of annual fishing mortality rates for the plot of scallops in the Mid-Atlantic Bight. The pattern of rotational fishing is also evident here, with three production cycles clearly recognizable within the 30-year time frame. The initial conditions are the same as those assumed for Georges Bank, but the initial closure in the Mid-Atlantic runs for seven years as opposed to only five years in Georges Bank. The second cycle consists of an eight-year closure period followed by two years of intense harvesting (Years 19 and 20). Some exploitation also occurs in Year 21 ($F_c = 0.145$) and the fishery closes again from Year 22 through 27. Intensive harvesting is scheduled for the last three years of the simulation.

Table 10 shows the size composition of landings for each major harvesting event. It is clear that the function of the closures is to provide sufficient time for scallop growth such that harvests are primarily composed of the larger meat counts (under 10 and 11-20), just as was observed in Georges Bank. The longer closure periods in the Mid-Atlantic are necessary to compensate for the slower growth of scallops (see Table 5 and Figure 9).

Figure 10 illustrates the effect of closures and harvestings on biomass of the plot of scallops in the Mid-Atlantic Bight. Biomass is allowed to fluctuate between 2 and 11 kg/tow. Because both growth and recruitment rates[6] are lower in the Mid-Atlantic (see Table 5), biomass does not

[6] It is recalled that the recruitment rates used in the model correspond to weighed averages of the 1992-2000 time series (NEFSC 2001), calculated separately for each stock area.

accumulate to the levels seen in Georges Bank (Figure 8). The estimated NPV_{30} for a 680-nm^2 plot under rotational fishing was $94 million. Comparatively, a constant fishing rate $F_c = 0.2$ leads to an NPV_{30} = $81 million (a 14% decline). The 6-year ramped rotation approach with $F_c = 0.2$ as target fishing mortality rate (i.e, $F_c = 0$ for the first three years and $F_c = 0.32$, 0.40, and 0.48 in the ensuing three years) results in an NPV_{30} = $86 million (a 9% decline). The time averaged fishing mortality of the optimal harvesting schedule (Table 9) is 0.27.

Table 9. Optimal Levels of Fishery Exploitation (F_c) for a plot of Atlantic Sea Scallops in the Mid-Atlantic Bight Region.

Year	F_C	Year	F_C	Year	F_C
1	0	11	0	21	0.145
2	0	12	0	22	0
3	0	13	0	23	0
4	0	14	0	24	0
5	0	15	0	25	0
6	0	16	0	26	0
7	0	17	0	27	0
8	1	18	0	28	1
9	1	19	1	29	1
10	1	20	1	30	1

Table 10. Size composition of landings (percentage) in each harvesting cycle of the bioeconomic model of Atlantic sea scallops in the Mid-Atlantic Bight region.

Size category	Cycle 1 (Years 8, 9, 10)[a]	Cycle 2 (Years 19, 20)	Cycle 3 (Years 28, 29, 30)
Under 10	39 %	33 %	27 %
11-20	43 %	47 %	49 %
21-30	9 %	11 %	12 %
31-40	4 %	4 %	5 %
41-50	3 %	3 %	4 %
51-60	1 %	1 %	2 %
61+	0 %	0 %	0 %
Total	100 %	100 %	100 %

[a] The numbers in parenthesis indicate the years in which harvesting takes place.
Numbers may not add up due to rounding.

Figure 9. Comparative growth of Atlantic sea scallops in Georges Bank and the Mid-Atlantic Bight.

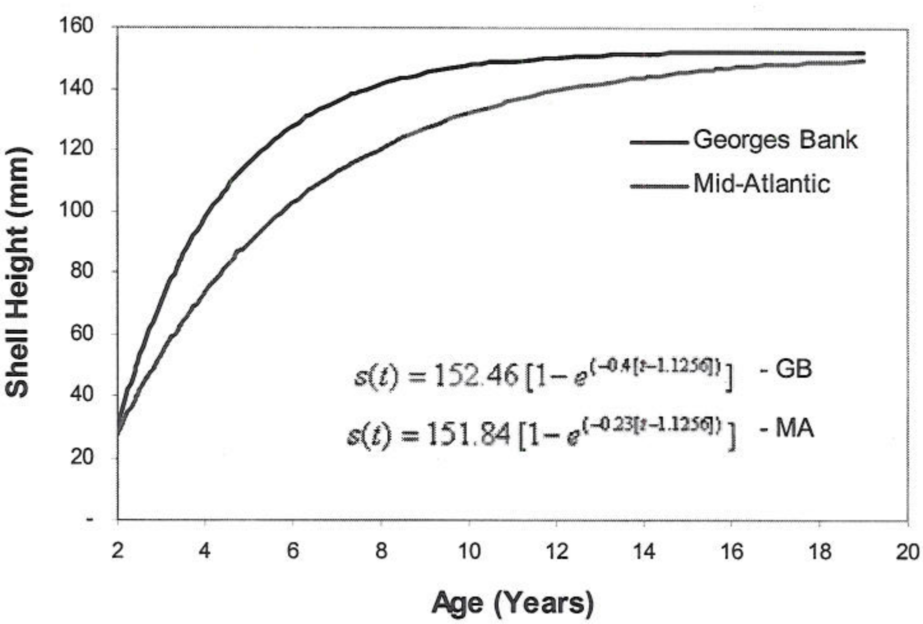
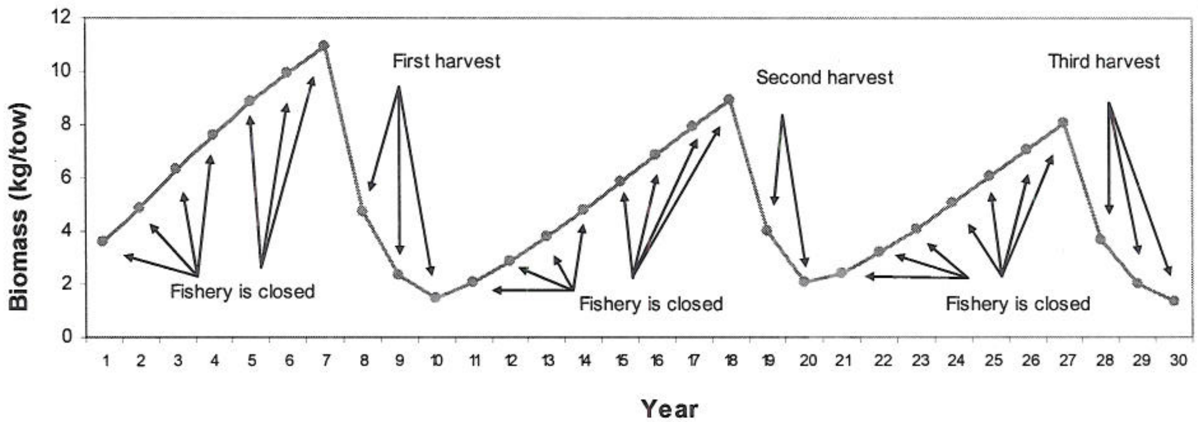


Figure 10. Biomass at the end of the year (kg/tow) as simulated in the bioeconomic model of the Atlantic sea scallop fishery in the Mid-Atlantic Bight region.



Effect of Variability in Annual Recruitment Rates

As explained previously, constant recruitment rates were assumed to facilitate the optimization of harvesting schedules. However, recruitment processes are stochastic, greatly influenced by environmental conditions, and with large variations normally occurring from year to year. To incorporate the stochastic effect of recruitment in our analysis, we conducted a series of Monte Carlo simulations comparing different patterns of exploitation for the fishery while allowing variation in annual recruitment rates. To this end, annual recruitment was modeled using lognormal distributions in each stock area (Georges Bank and the Mid-Atlantic Bight). The assumed mean and variances were estimated from the historical time series between 1992 and 2000 (NEFSC 2001) and are shown in Table 11.

Four patterns of exploitation were compared in the Monte Carlo analysis: 1) constant fishing at $F_c = 0.20$; 2) a three-year rotation with $F_c = 0, 0.2, 0.2$, which is the rotation program recommended by FA 16 for Closed Areas I, II and the Nantucket Lightship Area in Georges Bank; 3) a six-year ramped rotation with $F_c = 0, 0, 0, 0.32, 0.4$, and 0.48 (i.e., target fishing mortality rate is 0.2); and 4) the optimal harvesting schedules from Tables 7 and 9. Each Monte Carlo simulation was conducted for 400 trials.

The mean and standard deviation of the NPV_{30} outcomes from the Monte Carlo simulations are shown in Table 12. The results are qualitatively the same as those obtained under the constant recruitment assumption. The highest expected NPV_{30} values are achieved with the optimal rotation schedules from Tables 7 and 9. These schedules are clearly superior to the strategy of continuous fishing at $F_c = 0.2$ and the three year rotation propcsed in FA 16 for the closed areas of Georges Bank. Excluding the optimal rotation schedule, the best results are achieved with the six-year ramped rotation. In Georges Bank, the optimal rotation led to a relatively greater variability in NPV_{30} values; dispersion was about the same in the Mid-Atlantic. The greater variability in Georges Bank is related to strong recruitment events that have occurred in some of the closed areas.

Table 11. Mean and standard deviation of recruitment time series between 1992 – 2000 used in the Monte Carlo simulation of the Atlantic sea scallop fishery. Recruitment is expressed as annual number of recruits per tow.

Stock area	Mean	Standard deviation
Georges Bank	136.52	393.83
Mid-Atlantic Bight	108.13	203.5

Table 12. Mean and standard deviation (in 1996 million Dollars) of the distribution of NPV_{30} resulting from the Monte Carlo simulation (400 trials) of annual recruitment rates.

Stock area	$F_c = 0.2$, continuous		$F_c = 0, 0.2, 0.2$		Ramped rotation[a]		Optimal rotation[b]	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Georges Bank	285	116	260	116	302	122	338	196
Mid-Atlantic Bight	89	28	84	23	93	24	100	26

[a] This is a six-year rotation with $F_c = 0, 0, 0, 0.32, 0.4, 0.48$, respectively.

[b] See Tables 4 and 6.

Additional Implications for Management

All simulations conducted in this analysis provide conclusive evidence that the Atlantic sea scallop resource can be more efficiently managed under rotational harvesting than under any other management scheme involving continuous fishing activity. An important result is that net present value of the fishery is maximized *even if* (and more precisely, *because*) no fishing at all occurs for several years in a row. This, of course, does not imply that the entirety of the open areas in Georges Bank and the Mid-Atlantic Bight should be closed down for several years to let biomass accumulate. Given that our results suggest optimal closure periods of six and eight years followed by two years of harvesting, a sensible proposal would be to subdivide the stock areas in both Georges Bank and the Mid-Atlantic into eight and 10 sub-areas, respectively, and implement a program of rotational harvesting of these sub-areas. Because re-opened sections can support exploitation for two years in a row, fishing could take place in two sub-areas within Georges Bank and the Mid-Atlantic during any given year.

It is obvious that many other details would need to be addressed before implementing rotation of fishing grounds for sea scallops (e.g., harmonization with the fishery management plans for other species) but the important point is to recognize that rotation should be the underlying management paradigm for this resource. In other words, allowing fishermen to roam freely in open areas at all times clearly leads to a wasteful utilization of the resource. The difference in growth rates between Georges Bank and the Mid-Atlantic indicate that the strategy of rotational harvesting is robust to uncertainty in the true values of these parameters. This is important because the growth parameters of the Von Bertalanffy growth equations (Equation 13) are routinely subject to revisions based on the results of annual biological surveys (NEFSC 2001).

Spatial management of rotational areas at a high resolution level as set forth in Amendment 10 is a praiseworthy initiative but full-scale implementation may impose an overwhelming administrative burden on management agencies. Flexible boundaries might also generate confusion among fishermen. A simple scheme of mechanical rotation (that includes all fishing grounds) based on 6-year and 8-year closure periods in Georges Bank and the Mid-Atlantic

Bight may be a much more effective way towards sustainable management of the resource and improved profitability for the fishery. The mechanical rotation strategy proposed in FA 16 (Table 4) is an important step forward; however, the one-year closure period falls short if the objective is to rebuild biomass in a previously open area or to maximize economic returns from the fishery.

Logically, rotational schemes could be adjusted if new information becomes available, such as the identification of "nursery" areas with high production of recruits. Also, our model considered $F_c = 1$ as an upper bound for fishery mortality. Rotational strategies could be designed with a lower cap on fishing pressure if the objective is to maintain biomass at every moment above a specified level. However, our simulations for Georges Bank showed that setting $F_c = 1$ as an upper bound keeps biomass above the critical levels observed during the early 1990's for Closed Area I (Figure 8).

There are some other benefits associated with rotational management that were not addressed in this analysis. In addition to reductions in DAS, rotational management also leads to reductions in contact time between scallop gear and the ocean bottom. This has the important implication that amounts of bycatch should be lower under rotational fishing, a desirable management goal from any perspective. Another interesting aspect is that, while no definitive stock-recruitment relationship has been verified for Atlantic sea scallops due to the great influence of environmental factors on recruitment, recent evidence from the Mid-Atlantic suggests that area closures may contribute to boost recruitment. This additional effect appears to be likely and would further the case for rotational management.

4. CONCLUSIONS

The bioeconomic model presented in this paper provided compelling evidence that optimal exploitation of a resource with the life-history characteristics of Atlantic sea scallops (a sedentary species with fast growth and low natural mortality) involves rotation of fishing grounds. The traditional management approach of open areas with unrestricted access which ruled the fishery for decades is not appropriate for Atlantic sea scallops; such an approach eventually leads to the dissipation of economic rents from the fishery and ultimately creates the conditions for overexploitation of the resource.

The rotational management strategy appears to be robust to a number of assumptions regarding the life history of the resource, such as growth rates and uncertainty in recruitment rates. The essential idea for management of the resource is to institute closure periods that are sufficiently long to create a harvestable biomass composed primarily of large scallops, which demand a premium price in the marketplace. Extraction at high standing biomasses is also advantageous because it leads to reduction in operating days at sea and decreased contact time with the ocean bottom. The gains derived from closures of the fishery largely outweigh the initial loss of revenue.

Fishery management agencies should be commended for redirecting their attention to rotation as the new paradigm for management of the resource. However, the mechanical rotation strategies proposed so far involve closure periods that are too short relative to what is recommended by our model. Our results also indicate that the resource can support more intense exploitation upon re-opening of the closed areas. In other words, re-opened areas can be harvested at fishery mortalities larger than 0.20, the target fishing mortality rate typically recommended to maximize yield-per-recruit in models of continuous exploitation.

Our recommendations imply a thorough re-thinking of the way scallop fisheries have been normally conducted. Our main tenet is that scallops should not be managed in the same way as a mobile resource such as pelagic, free-swimming species. Scallops lend themselves to be managed in the same manner as forests or terrestrial crops are. We are aware that full-scale rotational management of Atlantic sea scallops would limit the ability of fishermen to decide where and when to fish. But fishermen must also realize that some of this independence must be given up if the ultimate goal is to achieve a more rational utilization of the resource. The rewards for this and future generations will more than compensate for the few sacrifices involved.

5. ACKNOWLEDGEMENTS

We would like to thank Dr. Steve Edwards (NMFS/NEFSC) for providing detailed landing statistics for the period 1998–2003. We are also indebted to Deborah Hart (NMFS/NEFSC) for offering important insights on the application of Holling predation models to the Atlantic sea scallop fishery. Assistance from Kurt Schnier (University of Rhode Island) was instrumental for the development of the MATLAB codes.

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